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Geotechnical and Geo-Environmental Damage and its Impacts on Critical Community Infrastructure during the 2021 Western European Floods: The Case Study of Altenahr, Germany

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ABSTRACT

Floods, often triggered by heavy rainfall or snowmelt, are the most common natural disasters worldwide. The 2021 Western European Floods (Germany, Netherlands, Belgium) provided the opportunity to study geotechnical and geo-environmental flood damage within the impacted areas throughout two separate reconnaissance missions and data collections visits (Aug 2021 and March 2022). This case study provides an overview of reconnaissance observations and field measurements specific to infrastructure in Altenahr, Germany. The role of river-soil-structure interaction and local geological conditions on the extent of flood damages, as well as the rehabilitation of flood-damaged areas around the town of Altenahr, and the well-known Altenahr roadway tunnel entrance/exit areas are discussed. Local failure observations, damage patterns, and measurements are presented and compared with general observations recorded in the remainder of the flooded Ahr Valley region. Reconnaissance data collection methods included LiDAR and structure-from-motion from unmanned aerial vehicles, sediment sampling, multispectral imaging, soil strength testing (in and out of water), riverbed imaging through side scan sonar imaging, bathymetric mapping using single beam sonar, and mapping of in-water deposits from low-frequency acoustic surveying. An overview of available data, data access, and ongoing/future studies using the information collected will be presented.

Keywords: 2021 Western European flood, infrastructure damage, reconnaissance observations, Altenahr Germany

1 INTRODUCTION

From 1995-2015, floods comprised 43 % of all natural disasters worldwide (UN/CRED, 2015) and a rise in mean global temperatures has and will continue to increase extreme rainfall events across the world (Tabari, 2020; Ingram, 2016; IPCC, 2013, Trenbeth, 2003). According to floodlist.com, the month of July 2021 represented the year's worst flood month on record with over 920 casualties in floods, landslides, and other rain-related incidents worldwide (Davies, 2021). While several areas in Germany (e.g., Valley of the river Ahr - "Ahrtal" (2016), Swiss Saxony National Park "Sächsische Schweiz" (Elbe River flooding, 2002), or the Oder River flooding, "Oderhochwasser" 1997) have historically experienced multiple significant flood events, the July 2021 Western European flood is considered the deadliest flood in recent German and European history since the early 1990s. Figure 1 depicts the historical death toll of major flood events over the last two decades on European grounds. The 2021 event surpassed previous upper limits by approximately threefold.

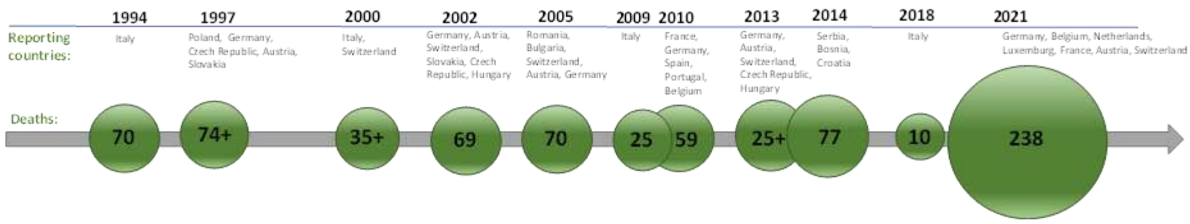

Figure 1. *Deadliest floods in Europe over the last two decades*

Over a period of two days (July 14-15th, 2021) the low-pressure system "Bernd" stalled over Western Europe, leading to record-setting rain over Belgium, Germany, Luxembourg, Switzerland, France and the Netherlands, with local precipitation volumes of up to 240 l/m^2. Approximately 40% of all flood gauges along the Ahr, Erft, and Urft rivers in Germany exceeded their highest information level, in some cases significantly. Many water level gauges suffered severe damage (Figure 2) and were quickly, albeit provisionally repaired to provide continued short-term flood warnings and water level data following the flood event (LANUV, 2021).

Considerable damage to the built environment included residential houses, motorways and railway lines, bridges, and other essential facilities (e.g., industrial plants, wastewater treatment plants, power transmission structures, and telecommunication facilities). Road destruction and closures left many areas inaccessible for days, cutting off villages from evacuation routes and emergency response units. Estimates by the German reinsurance and risk analysis company Munich Re suggest flood related damages in Germany to accumulate to $US 54 billion, with only $US 13 billion of insured losses (Statistika, 2023). Based on global assessments by Munich Re, this level of damage currently ranks 2nd highest amongst all natural disasters in 2021, only preceded by Hurricane Ida (USA) in Aug/Sept 2021 with a total amount of $US 65 billion in damages.

Despite the previous and costly floods in Germany along the rivers *Oder* in 1997 and *Elbe* in 2002, Germany's National Flood Protection Program was not commissioned until 2013, and its implementation has been slow (Bund, 2021). State agencies do not only attribute part of the 2021 damage extent to insufficient flood mitigation strategies, but also recognize the mismanagement of catchment areas of streams and rivers with an increase of impervious surfaces to significantly contribute to flash floods and widespread inundation in cities (Bund, 2021). Consequently, changing land surface conditions did not only exacerbate the impact of the 2021 flood event, but make future flood and damage predictions more challenging, as past experiences and knowledge are likely less applicable in preparing future flood resilience. Similarly, engineering design and analyses of critical infrastructure components require new performance considerations aside from traditional dead and live loads to recognize and include load scenarios driven by short and long-term natural hazards. In a recent U.S.-based study, Li et al. (2022) demonstrated that flash flooding is becoming 7.9% more extreme, including higher peak flows and faster arrival times, which poses unprecedented threats to the performance of infrastructure in flood-prone areas. While flood risk maps have been developed for most of Germany's rivers including the Ahr and the Erft rivers (Landesamt für Umwelt, Rheinland-Pfalz, 2021; Landesamt für Natur, Umwelt und Verbraucherschutz, Nordrhein-Westfalen), the 2021 scenario, which was assigned a very low probability of occurrence based on predictions of historical events on German grounds, was substantially exceeded by the July 2021 flood event and suggests the peak flow return period of the Ahr flood event to be 1 in > 500 years.

Within the impacted areas of Germany, Belgium, and the Netherlands, the Geotechnical Extreme Event Reconnaissance (GEER) Association, conducted two reconnaissance missions in which damage observations were recorded and perishable field data was collected using portable small-scale devices. The two deployments allowed for invaluable insight about the 2021 flood event to advance our understanding of the vulnerability of the existing geo-infrastructure, improvements needed for design and construction practice, and overall urban resilience of flood-prone communities. These lessons are critical to develop enhanced risk mitigation strategies for urban and rural settings and can be advantageous for future extreme events, regionally and globally. To maximize the reconnaissance coverage of affected sites, density, and diversity of data collected, a variety of remote sensing technologies including aerial and mobile phone photography, terrestrial LiDAR, multispectral photography, and optical satellite imagery were utilized. Mobile device photography was used for the purpose of rapid documentation. Aerial photography provided different vantage points of features of interest and allowed for larger spatial coverage and manoeuvrability. UAV Structure from Motion (SfM) technology permitted building of three-dimensional (3D) point clouds and meshes, digital elevation models (DEM), orthomosaics, and optical panoramics of features of interest. Furthermore, within the areas of damage, soil samples were obtained at sites of particular interest. A complete description of- and access to all data collected and curated during the reconnaissance mission can be found in Lemnitzer et al. (2022), and Stark et al. (2022), respectively. These resources are available publicly and free of charge.

The 2021 flood offered a multidimensional perspective on the interaction between hydrological, structural, geotechnical, geomorphological, and hydrodynamical performance of built environments in regions with severe flood hazards. Hereafter, we present the case study of Altenahr Germany, as documented by the GEER reconnaissance team, with a focus on geotechnical and geo-environmental performance aspects within Altenahr and its surrounding areas. We also introduce several sets of data collected, the opportunities that these data sets can provide for future analyses and research studies.

Altenahr is a small district with a population of 1914 people in the county of Ahrweiler. The district consists of four smaller municipalities, namely Altenahr, Altenburg, Kreuzberg, and Reimerzhofen. However, most often all four municipalities are combined and referred to as Altenahr. The district as well as the individual municipalities of Altenahr were heavily featured in various media sources due to their extensive flood damage to infrastructure and the total number of fatalities (33), which was the second highest reported amongst any of the single districts (Schmid-Johannsen et al., 2021). Altenahr has an elevation of about 170m above sea level, and an area of 15km^2. The Ahr bend (Ahrschleife) in Altenahr, a tight meander wrapping around central parts of the town, contributed substantially to the heavy, localized damage and high number of fatalities. The water level gauges along the Ahr in Altenahr exceeded its previous record of 2016: 3.71 m, discharge: 236 m^3/s (Schaefer et al., 2021). In July 2021, the measuring stations broke due to flooding at a value of 5.05 m (and a discharge of 332 m^3/s). Estimates for this event suggest a water level between 7 and 8 m, (in selected locations up to 10 m, Figure 2) with a discharge between 400 and 700 m^3/s. Compared to the two particularly significant flood events previously recorded in the Ahr valley in 1804 and in 1910, the 2021 event suggests lower flood levels than in 1804 (estimate: ~ 1100 m^3/s), and similar magnitudes as in 1910 (~ 500 m^3/s) (Schaefer et al., 2021).

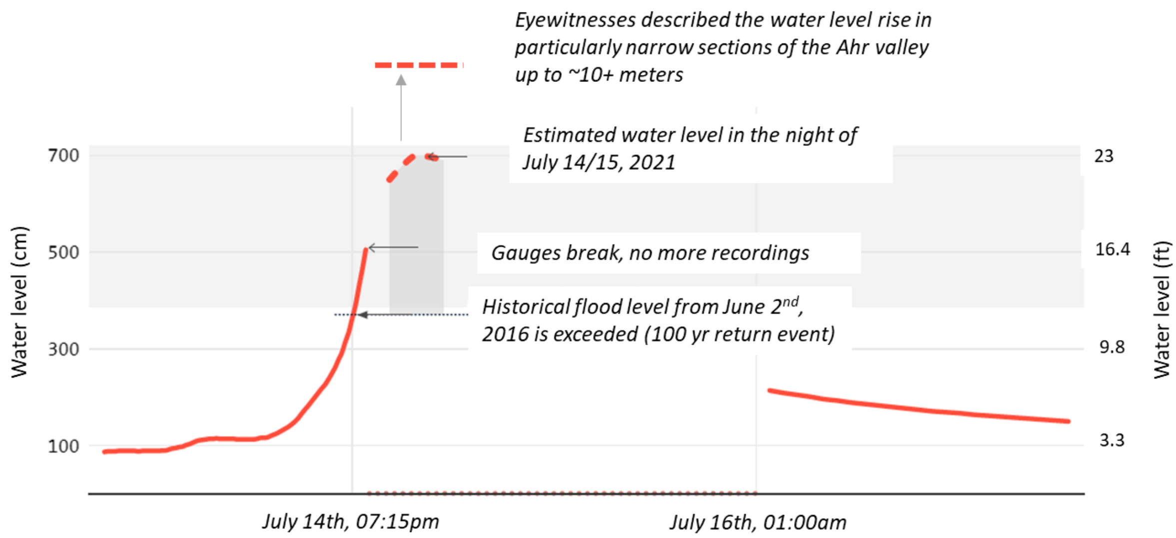

Figure 2. *Water level rise during flood event in the district of Altenahr and loss of gauge readings (adapted from Schmid-Johannsen et al. (2021), data obtained from Hochwasserzentrale RP (2021))*

2 CASE STUDY: ALTENAHR, GERMANY

2.1 Altenahr, Germany: Overview of residential and infrastructure damage in the town center

Figure 3 depicts an aerial image of Altenahr. The yellow shaded areas experienced severe damage with partial to full destruction of residential, commercial, and transportation infrastructure. Furthermore, these areas experienced soil erosion, particularly near the sloped Ahr riverbanks, as well as sediment and debris re-deposition. In total, the Altenahr district reported 480 (80%) of all residential buildings to be heavily damaged (SWR.de, 2022). Approximately 150 of the 480 affected buildings had to be (or will be) demolished due to severe water damage and/or oil contamination, and many of them will not be given permission to rebuild in the same location due to the newly published inundation maps. Reconnaissance observations suggest the primary damage was associated with building facades, damage to lower floors due to the impact of wood and debris transported by the flood waters, as well as soil erosion near the foundation level. Figure 4 depicts examples of damage to residential buildings in Altenahr. Typical story heights in Germany are approximately 2.30m, suggesting water levels reached at least 4.0 m in many parts of Altenahr, as indicated in Figure 4. Besides the frequently observed above-ground damage shown in Figure 4 (top), Figure 4 (bottom) also depicts the remains of a washed-out residential structure, with only basement walls remaining. This failure scenario suggests acceptable geotechnical/foundation performance but indicates the lack of structural connection between the basement walls and the floor slab at the ground level (e.g., lack of continuous rebar). Several similar examples were observed in other regions of the Ahr valley, however, this type of extreme failure was less frequent than facade damage/ or removal of only parts of the superstructure.

Figure 5 shows the Ahr river at the Altenahr train station, a transportation key point for the Ahr Valley tourism. The station (building to the right in Figure 5) was situated between a river meander (outer bend) and steep hill slopes (consisting primarily of rock cuts) as shown in Figure 5. Substantial riverbank erosion, damage and washout of an earth retaining wall can be seen in this photograph. Likely due to the unfavorable location of the station, slope armoring and stabilization was not effective in preventing extensive damage to the riverbanks immediately adjacent to the train station.

Out of the 17 bridges in the Altenahr district, only one bridge remained intact. The Altenahr road bridge, located in the town center (labelled in Figure 3 and photographed in Figure 6) remained structurally functional, allowing for post-flood traffic to resume normally upon clean-up and debris removal. This performance can be attributed in part to the favorable boundary conditions at the bridge ends. As shown in Figure 6, the bridge is connected with/to a continuous earth retaining wall (Fig. 6 top right) or has a wingwall, which prevented floodwaters from reaching behind the bridge abutment area and washing out backfill materials (as observed in many other locations). The other bridge end (shown in Figure 6 top left, center and bottom) was connected with the adjacent road through an integrated retaining wall with deck (Fig. 6 middle/bottom). Figure 6 shows the bridge at the time of the reconnaissance visit (top), the pre-flood condition (center), as well as eight months after the flood event during a second visit of the reconnaissance team (bottom, March 2022).

Figure 3. *Aerial map of Altenahr with heavily flood damaged areas.*

Figure 4. *Example of structural/residential damage in Altenahr (town).*

Figure 5. *Soil erosion and retaining wall failure at the Altenahr train station.*

Figure 6. *Photographs of the only structurally intact bridge in Altenahr following the flood, Top: Photos of abutment regions of the bride in Aug 2021, Middle: Pre-flood aerial photograph, Photo Credit: Heinz Grates (https://www.aw-wiki.de/w/index.php?curid=36263), Bottom: Aerial photo taken by the GEER team in March 2022, showing the bridge after clean-up work.*

2.2 Altenahr: The tunnel entrance and exit site

The tunnel exit site in Altenahr has been one of the most featured damage locations of the Ahr valley in Germany. Figure 7 shows an aerial map obtained from Google Earth and various infrastructure facilities near the affected site. This location is of particular interest for documenting how soil relocation near the tunnel and intersection with the Ahr river relate to local hydraulics, geology, and abundant infrastructure. The location features multiple key infrastructure items forced to be tightly grouped due to the restrictive, steep valley, and the river. The presence of this infrastructure, in particular the tunnel, led to a significant change in local hydraulics.

The *Ahr* river makes a bend around the tunnel (which is located south of the photo, but not visible in Figure 7). Aside from the tunnel entrance and exit areas, Figure 7 also describes the infrastructure around the tunnel and its performance during the flood. Flood waters flowed through the tunnel from the tunnel entrance on the west side, nearly filling the opening cross-section. The relatively small cross-sectional opening of the tunnel caused a high-velocity water efflux that exited on the east. The double bridge (rail/bicycle) on the west side of the tunnel was also destroyed during the flood.

Figure 8 (top) shows a Google Street View of the tunnel exit in May 2021 prior to the 2021 flood event, followed by a reference photograph of the tunnel exit during the 100-year return flood in 2016 (Fig. 8 (top, right)). Figure 8 (bottom) shows the tunnel exit and surrounding area on August 13, 2021, approximately four weeks after the flood. The tunnel street (Tunnelstrasse) was completely destroyed by the water efflux rushing out of the tunnel exit and exposed underlying bedrock to depths of 9 m. Figure 8 (bottom) also shows the jointing orientations in the underlying rock, damage to the adjacent residential buildings, and the large volume of material that was eroded downstream of the tunnel exit. The eroded crater-like feature outside the tunnel exit had approximate dimensions of 9 m in depth and 50 m in width. A similar feature was documented during the 1910 flood at the east side of the tunnel (Gaertner, 2022).

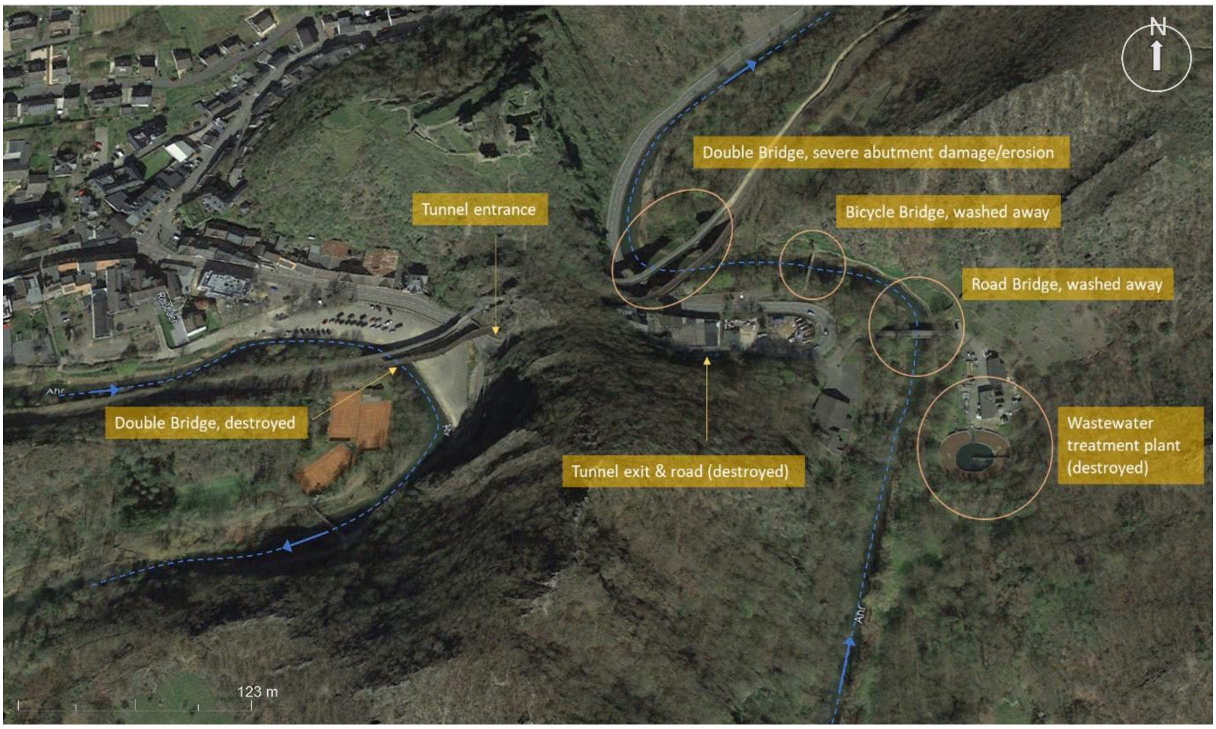

Figure 7. *Google Earth Aerial View of the tunnel entrance/exit site in Altenahr prior to the flood (3/2020).*

Figure 8. *Top left: Google Earth/Maps Street View of the Altenahr tunnel from May 2021; top right: photo during the June 2016 flood event (Source: https://www.altenahr.de/index.php?id=26&publish[id]=9709&publish[mode]=overview&no_cache=1#18); bottom: photos by the reconnaissance team after the 2021 flood, August 2021 (50.5165261, 6.9975355)*

Near the tunnel exit, a double bridge connected railway tracks and a road across the Ahr river. Figure 9 shows the severe damage to both bridges, but also the extent of sediment relocation and streambed destruction at this location. The image also illustrates a key geological and topographic characteristic of the Ahr valley: its steep slopes and limited width of the river valley. This topography has been highlighted as a key issue that led to the severity of the flood in the Ahr valley. Figure 10 shows an elevation profile at the location of the double bridge and surrounding area. The bridge is situated near profile #2 in Figure 10 (right). The maximum slope of the adjacent hillside was approximated as 76.9% (cross-section 2). Figure 10 also illustrates the extent and width of soil erosion and sediment redeposition along the Ahr river in the vicinity of Altenahr (Fig 10, left).

Figure 9. *Aerial photograph of the double bridge (rail/road) at the tunnel exit Altenahr*

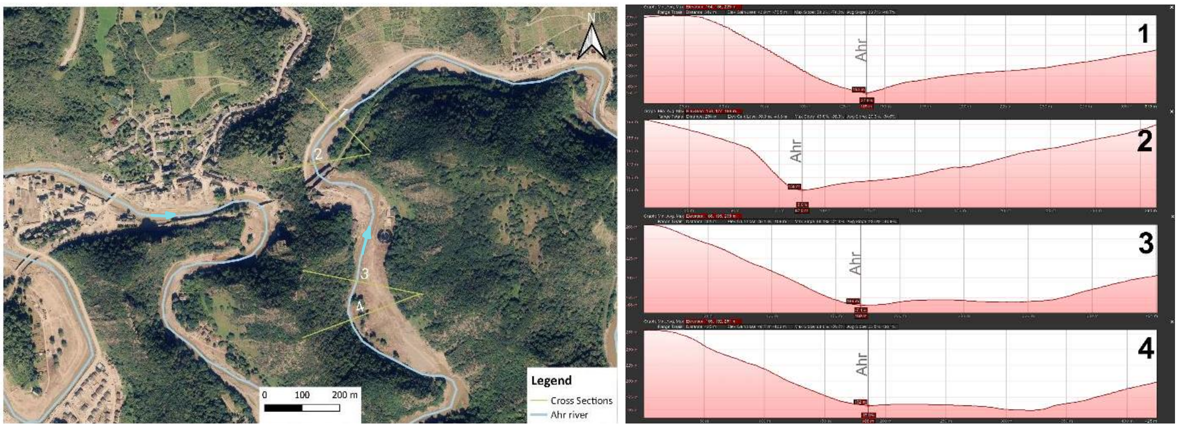

Figure 10. *Left: Plan view of tunnel exits and location of cross-sections; Right: Elevation profiles in near vicinity of the Altenahr tunnel exit*

The bridge has a total height of 18 m, and a length of 100 m. The bridge arches have a clear cross-section of flow of nearly 33 m in width and 15 m in height. The bridge piers have a thickness of 5.3 m and an enlarged sloped reinforced mantel at the bottom of the piers. The bridge was placed on shallow reinforced concrete footings. No structural damage was observed at any of the intermediate bridge supports. A comparison of before-after imagery (Figures 9, 11) suggests the pre-flood channel of the Ahr river through the middle arch of the bridge (Figure 11, left), while the immediate post-flood route of the river occurred primarily through the left arch of the bridge as shown in Figure 9. This left side of the bridge was the most severely affected, with substantial erosion and damage to the abutment region (Figures 9 and12, left). Following restoration and clean-up work in the area, the river was guided back into its pre-flood channel (Figure 11, right).

Figure 11. *Before and photos of double bridge at tunnel exit taken in upstream direction, photo credit: Heinz Grates, Source and access at https://www.aw-wiki.de/w/index.php?curid=67031; Left: Pre-flood, Right: Post Flood and post-river rerouting back into its original riverbed*

Figure 12 shows close-up photos of the abutment region around the double bridge. The extent and elevation of the washed-out abutment area provides an estimate of the water elevation (~18 m above its original water level) within this narrow stretch of the valley. Remainders of the damaged train tracks span between the bridge and the adjacent hillside. The bridge abutment area in Figure 8 (left) consists of an un-engineered connection between the bridge arch and adjacent natural hillside, likely backfilled with excavation spoils at the time of construction. The lack of wingwalls and armoring likely contributed to the extensive erosion in the vicinity of the abutment. However, the large cross-sectional flow area of the bridge arches and additional flow area created by the abutment erosion likely mitigated structural damage to the bridge structure itself.

Figure 12: *Photo of the abutment region of the double bridge, August 13th, 2021. Left: Washed out abutment area, Right: bridge abutment area intact and connected to adjacent rock slope*

In September, 2022 the tunnel exit was reopened following road construction of nearly 2.43 Million Euros. Four adjacent residential structures were removed (Gaertner, 2022). According to city officials, the extent of future flooding is expected to be less due to increased asphalted surfaces near the tunnel exit and due to lack of easily-eroded cobblestone sidewalks.

Figure 13. *Tunnel street at opening in September 2022*

In the background of Figure 9, a water treatment plant is visible which was also affected by the flood event. The water treatment plant (shown in Figure 14) was irreparably damaged (General Anzeiger, 2022), and wastewater was directly discharged untreated into the Ahr River according to authorities in Mainz, the capital of Rhineland-Paletine (RP). This incident was not isolated and the Altenahr treatment plant was one of several plants (including its canalization) that could not be repaired. Approximately 30 Million Euros were allocated for the reconstruction of sewers and wastewater treatment plants in the Altenahr district. However, this allocation is only a fraction of the more than 183 Million Euros needed to repair the major wastewater facilities within the Ahr valley and remediate wastewater-based environmental damage to the region (General Anzeiger, 2022). The wastewater treatment plant experienced flood water influx from both upstream and downstream directions due to (1) water flushing through the narrow stretches of the Ahr bend (upstream), and (2) water being backed up as efflux from the tunnel hits the steep slopes across the tunnel exit. The adjacent structure of the wastewater facility was also destroyed. Current estimates by government officials suggest that ⅓ of the canalization in the Ahr valley is damaged, destroyed, or entirely washed away. The restoration of the entire sewer system is expected to take 10 years. Small mobile wastewater treatment plants are currently being erected to prevent continued discharge of untreated water into the Ahr (SWR.de, 2021).

Figure 14. *Wastewater treatment plant Altenahr following the 2021 flood, Source: DPA/Thomas Frey*

2.3. Data collection and sample processing

The collection of perishable data immediately after extreme events remains challenging. Immediate repair and response needs, particularly in urban areas and areas with immediate utility and infrastructure needs, must have priority, and thus, reconnaissance missions with small, portable gear and focused on the collection of most perishable often represents the only opportunity to collect the data needed to investigate the detailed performance and failure mechanisms. The excerpt and initial data presented hereafter provides a glimpse into the information that was collected during the reconnaissance missions after the flood events in July 2021 and March 202 in Germany. Table 1 presents a summary of techniques employed during the field investigations and the corresponding data/information to be gained. Figures 15 and 16 provide selected examples.

Table 1: Overview of data collection techniques and measurements obtained

Data collection techniques	Objectives / information to be gained?
UAV imagery *(stand-alone photographs)*	overview of ground conditions from various aerial vantage points
UAV imagery *(continuous image recording)*	structure for motion modelling (SfM)
LIDAR *(ground)*	terrestrial based digital elevation models of man-made and natural features
LIDAR *(aerial)*	aerial based digital elevation models of man-made and natural features
Hand-held photography *(Cameras, mobile devices)*	rapid documentation of in-situ observations
Multispectral imagery *(aerial, attached to UAV)*	detection and characterization of above- and subsurface objects through multi-band spectral imaging; example: characterization of sediment deposits
Multispectral imagery *(on ground, camera operated hand-held)*	
Soil Sampling *(traditional collection of disturbed samples)*	laboratory standard classifications and grain characteristics, soil strength
Pocket penetrometer *(hand-held, portable)*	estimates in situ unconfined compressive strength of cohesive soils
Moisture meter *(hand-held, portable)*	estimates in situ moisture contents
Z-boat *(manually or remotely operated, in water)*	hydrographic surveying
Side-scan sonar *(hand-held, lowered manually from support boat)*	high frequency acoustic pulse measurements for riverbed imaging
Single beam sonar *(hand-held, lowered manually from support boat)*	bathymetry mapping, determination of water depths
Low frequency echo sounder *(hand-held, lowered manually from support boat)*	acoustic surveying for mapping of in-water deposits

Figure 15 depicts an excerpt of initially collected 3D point cloud data of the double bridge using terrestrial LiDAR. Data processing from this location (as well as most others) is still ongoing. The generation of the point cloud model from terrestrial LiDAR allows for geometric measurements of features of interest. As shown in Figure 15, estimates of the total bridge height, clearance height, and cross-sectional distance of the river were found to be 17.96m, 14.72m, and 45.50m respectively. Similar measurements are possible in point clouds generated from UAV imagery, albeit with less accuracy. Aside from measurements depicted in Figure 15, possible future geometric measurements include volume of soil lost due to scour and erosion, angle of pier tilt, deck deflection, and the dimensions of resulting cracks in decks or piers. These data provide meaningful information for numerically modelling water-structure-soil interaction at the bridge location.

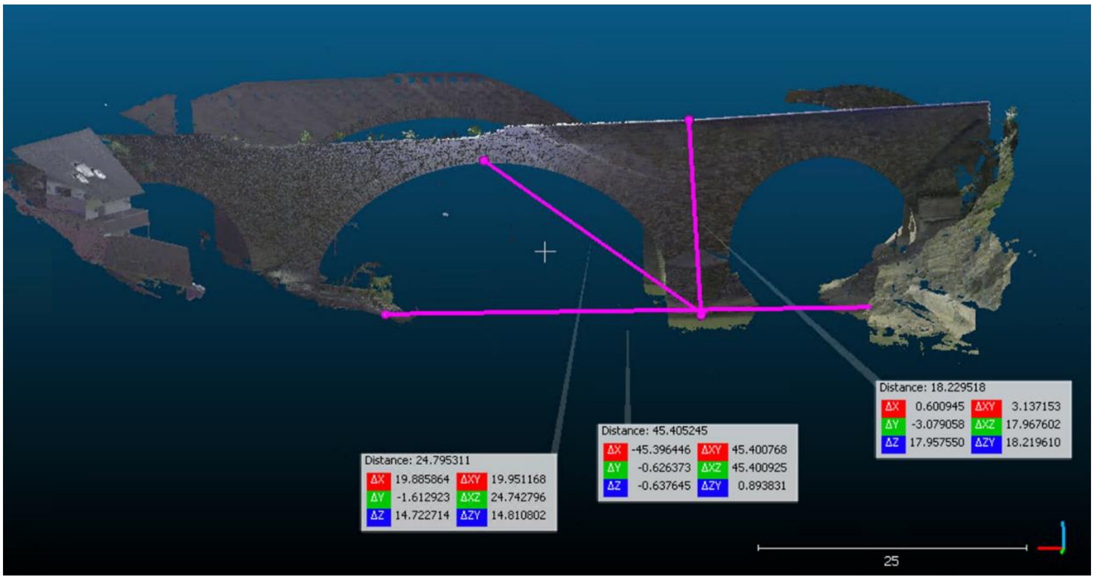

Figure 15. *3D point cloud excerpt derived from terrestrial LiDAR at the Altenahr double bridge.From left to right, measurements of the bridge clearance height (delta Z = 14.72m), river cross sectional distance (delta X = 45.50m), and total bridge height (delta Z = 17.96m) were measured using the LiDAR derived point cloud.*

At five selected locations in the Ahr Valley, including in Altenahr, in-water measurements including bathymetry and riverbed sediment classification were performed using different geo-acoustic surveying tools (single beam sonar, side scan sonar, low-frequency chirp sonar), physical testing of riverbed sediments using a portable free fall penetrometer, and sediment sampling. Figure 16 (left) shows the deployment of a remotely operated vehicle equipped with a single beam sonar for bathymetric measurements, as well as the terrestrial lidar system used. Figure 16 right shows sediment sampling of flood deposits. Both images represent a severely damaged double bridge site just upstream of entering the town of Altenahr center. While this data is still in processing, it will provide seamless data sets connecting subaerial topography and subaquatic bathymetry to enable a full picture of sediment relocation during the flood event. Also, scour depths around bridge piers and abutments were determined. Most significant sediment deposition sites were easily identified by surficial fine-grained soft sediments, while erosion hotspots represented significant bathymetric features, or bedrock, cobbly and gravelly surfaces stripped from any more mobile sediments. The combination of subaerial to subaquatic elevation mapping and sediment characterization represents a unique data set for water-structure-soil interaction modelling and investigation of the detailed processes that resulted in the severe damages.

Figure 16. *Left) Deployment of Z-boat for bathymetric measurements in the Ahr river in just upstream of the town entrance of Altenahr. Right) Sediment sampling in the same location.*

3 SUMMARY

Considering changing trends in hydrologic patterns driven largely by global climate change, the understanding of critical infrastructure performance during extreme flooding events becomes crucial. A unique data set was collected during the post-disaster reconnaissance of the flooding in Western Europe in 2021 that enables further research into how different features interplay to make this class of events so destructive. Initial observations indicate the importance of considering how human activities and infrastructure may modify local hydraulics, potentially exacerbating water levels and discharge rates. Furthermore, built environments in the vicinity of river meanders can be subject to increased risks from flooding and erosion. Together with local geology, these issues jointly influence the spatial extent and severity of scour and erosion during extreme flooding. The unique data set collected as part of this reconnaissance provides valuable measurements of both subaerial and subaquatic information, towards a more complete view of the flood-infrastructure-soil interaction. This will enable comprehensive analyses that consider the joint influence of flooding characteristics, infrastructure design, and local geologic features.

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